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Radiative Climate Forcing by Anthropogenic Greenhouse Gas Emissions in Finland

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Abstract

Finnish greenhouse gas emission histories (CO_2, CH_4, N_2O, CFCs and substitutes) and some future scenarios are presented. The direct anthropogenic emissions from fossil and peat fuel use, agriculture and waste management are taken into account. In addition to these, the human-induced changes in the emissions and sinks of greenhouse gases from peatlands and forests are considered. The greenhouse impact of the emissions is expressed as global average radiative forcing. The impact caused by emissions in Finland is compared with global figures on absolute and per capita bases.

At the moment the Finnish direct anthropogenic contribution to the global radiative forcing is approximately 4 mW m^{-2}, most of which is caused by CO_2, while the global value is about 2.5 W m^{-2}. If the human-induced changes of the biosphere since the 1920's (forests and peatlands) are included, the net Finnish contribution is about halved. In the future, the radiative forcing caused by Finnish anthropogenic emissions will continue to increase, and will remain higher than the present value during the next century even if strict emission reductions are assumed (~ 3 % annually). The contribution of the biosphere remains significant in the future also in most considered scenarios, although its relative weight decreases.

Key words: greenhouse gas emissions, radiative forcing, climate change, global warming

1. Introduction

The increasing atmospheric concentrations of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) change the radiation energy balance of the earth. This change is called radiative forcing (*IPCC,* 1995). The radiative balance is also affected by the concentrations of CFCs and related compounds, ozone (O_3) and anthropogenic aerosol particles.

The Framework Convention on Climate Change (FCCC) aims at the stabilization of greenhouse gas concentrations in the atmosphere at such levels that they do not cause dangerous anthropogenic interference. Studies on the stabilization problem have been published for example in the 1994 and 1995 reports by IPCC (*IPCC,* 1995; *IPCC,* 1996). This work examines the radiative forcing caused by concentration changes. This

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allows us to examine different greenhouse gases on the basis of a common quantity. By using radiative forcing as the measure of the greenhouse impact, the dynamics of the phenomena can be represented more accurately than if all emissions are for example converted directly into CO_2-equivalents. Thus it is well suited for situations where the emissions and sinks of greenhouse gases are changing over time.

The Finnish contribution to the global greenhouse gas emissions and radiative forcing is small and approximately proportional to the share of the population. If the anthropogenic greenhouse impact is to be controlled, each country should take into consideration the radiative forcing caused by their emissions.

The objectives of this article are twofold. First we estimate the contribution of various anthropogenic greenhouse gas emissions and sinks in Finland to the radiative forcing and examine the dynamics included therein. On the basis of those results we compare the likely range of the Finnish contribution to the greenhouse impact with estimates of global radiative forcing on absolute and per capita bases.

2. *Estimation of the radiative forcing*

The global average radiative forcing in this article has been calculated using the REFUGE model (*Korhonen et al.,* 1993a; *Savolainen* and *Sinisalo,* 1994). The radiative forcing resulting from the emissions is calculated in two stages. First the atmospheric concentration change caused by the emissions is computed. In REFUGE the atmospheric CO_2 concentrations due to emissions can be computed with either a compartment type carbon cycle model (*Siegenthaler* 1983) or by using an explicit pulse response function. The latter method is mainly in use. For CO_2 the pulse response function

$$p(t) = 0.131 + 0.201e^{-t/362.9} + 0.321e^{-t/73.6} + 0.249e^{-t/17.3} + 0.098e^{-t/1.9} \qquad (1)$$

by *Maier-Reimer* and *Hasselmann* (1987) corresponding to present day concentrations is used here to describe the removal of excess atmospheric carbon by the oceans. Pulse responses from other models and concentration levels exist, but for our purposes the one given by eq. (1) is sufficient. Some sensitivity studies have been made with other functions and the compartment model (*Korhonen et al.,* 1993b). For the other gases (CFCs and substitutes, CH_4 and N_2O) a simple exponential decay model with a gas-specific constant lifetimes are used to calculate the concentration changes due to emissions (*Pipatti* and *Sinisalo,* 1994; *Pipatti et al.,* 1996). The response times used for the different greenhouse gases are shown in Table 1. The uncertainty of the concentration change calculations is on the order of ± 25 % due to inaccurately known carbon cycle for CO_2 and atmospheric lifetimes for the other gases.

Table 1. Atmospheric lifetimes of some greenhouse gases used in the concentration calculations (*IPCC,* 1995).

Gas	Mean atmospheric lifetime (years)
CH_4	14
N_2O	120
CFC-11	50
CFC-12	102
CFC-113	85
HCFC-22	13.3
HCFC-142b	19.5
HFC-134a	17.5

The concentration changes resulting from the calculations of stage one are then converted into radiative forcing using the gas-specific functions given in *IPCC* (1990) that have been derived from more detailed radiative transfer models. Only the direct radiative forcing is taken into account for most gases, but for CH_4 the indirect impacts have been taken into account by multiplying the results by 1.3. This factor represents an estimate for the indirect forcing due to methane-induced increase in the troposhperic ozone and stratospheric water vapor (*IPCC,* 1995). The radiative forcing functions are accurate within approximately ± 20% (*IPCC,* 1995).

Even though the absolute values of the radiative forcing calculations used here contain uncertainty on the order of ± 30% due to possible inaccuracies both in various assumptions in the radiative transfer modeling and in the concentration calculations, the inaccuracy in comparisons - e.g. when the forcings of the same emission scenarios at two different time points are compared - is much smaller. This is due to the fact that the sources of uncertainty correlate strongly, resulting in smaller relative uncertainty.

In the calculations of this study the background global greenhouse gas concentrations have been assumed to stay constant at present level. Since the background concentrations are in fact increasing, this leads to an overestimation of the future greenhouse impacts due to Finnish CO_2, CH_4 and N_2O emissions due to their nonlinear relationships between a concentration change and its radiative forcing. It would have been possible to assume some arbitrary development for the global concentrations e.g. according to IPCC IS92 scenarios (*IPCC,* 1992). However, this would complicate the interpretation of the results unnecessarily because it is likely that in practice the Finnish emission control scenarios are linked to global scenarios so that each Finnish scenario might have different global background concentration developments.

3. *Emissions and radiative forcing*

The estimated carbon dioxide emissions and sinks due to fossil fuel use and forest growth are shown in Fig. 1 (*Korhonen et al.* 1993a, *Kanninen et al.* 1993). The fossil CO_2 emissions have been minor until the fast growth during the last few decades. Three future scenarios (F_A, F_B and F_C) are shown. Scenario F_A follows the forecast of *Ministry of Trade and Industry* (1990) until the year 2025; thereafter it is a linear extrapolation. The scenarios F_B and F_C represent decreasing emission paths. The scenario F_B assumes a return to current emission levels by the year 2030 and an annual decrease of 1% thereafter. In case F_C the emissions are assumed to decrease by 25% by the year 2030, and by 3% annually thereafter. The 3% annual rate corresponds roughly to the renewal rate of the investments in the energy production system. Thus an annual emission reduction of 3% implies that all new investments in the energy system would have to cause considerably less CO_2 emissions than the old ones.

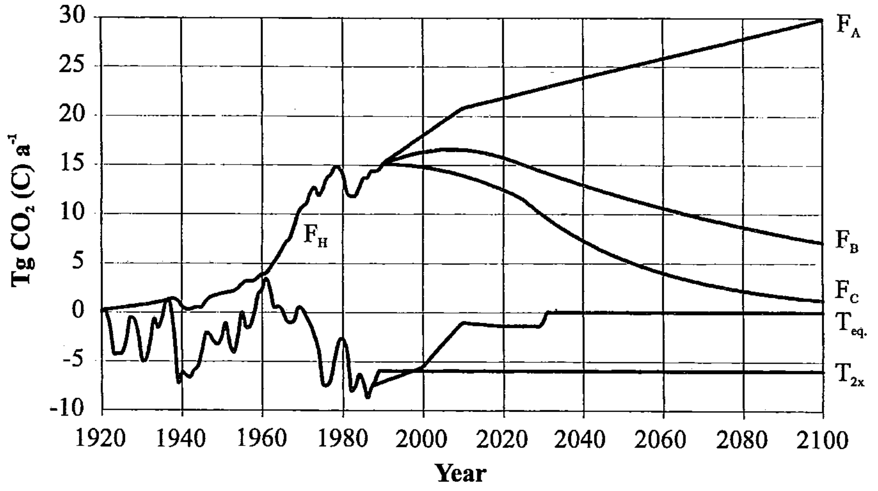

Fig. 1. Estimated carbon dioxide emissions from the Finnish fossil fuel use and sinks due to forest biomass net growth. Scenario F_A is extrapolated from the report by *Finnish Ministry of Trade and Industry* (1990). Scenario F_B assumes emissions decreasing by 1% annually after 2025, at which point the emissions are assumed to be at the current level. Scenario F_C assumes emissions decreasing by 3% annually after 2025, at which point they are 25% below current level. Scenario $T_{eq.}$ assumes equilibrium of forest growth and cuttings after the year 2030, and in scenario T_{2x} the carbon storage of Finnish forests is assumed to double from its present value.

The forest sink is known from the 1920s onwards and has undergone large variations over time (*Kanninen et al.*, 1993) mainly due to changes in cuttings. Two future scenarios $T_{eq.}$ and T_{2x} have been chosen to cover at least to some extent the uncertainty in the future development. In the first ($T_{eq.}$) one the tree growth and cuttings follow the forecast of *Ministry of Forestry and Agriculture* (1992) until the year 2030, and are assumed to be in equilibrium thereafter. In the other case (T_{2x}) it is assumed that the forest biomass doubles from its 1990 value by the year 2100. No change in the soil carbon content is assumed to take place. The future forest growth scenarios also assume that the Finnish forests are not adversely affected by the possible climate changes.

Uncertainty of recent fossil CO_2 emissions is some ± 10 % and it increases towards the beginning of the century. Compared to CH_4 and N_2O emissions, the fossil CO_2 emissions have been significant in Finland for only about 30 - 40 years, so the significant period of the fossil CO_2 emissions can be considered well known. The uncertainty of the carbon sinks in the forests is probably larger. The stemwood volume and its changes are known relatively well. The contribution of the other parts of the tree to the total biomass is assumed to be 75 % (*Kanninen et al.*, 1993). The radiative forcings calculated from the CO_2 emission scenarios (Fig. 1) are shown in Fig.2.

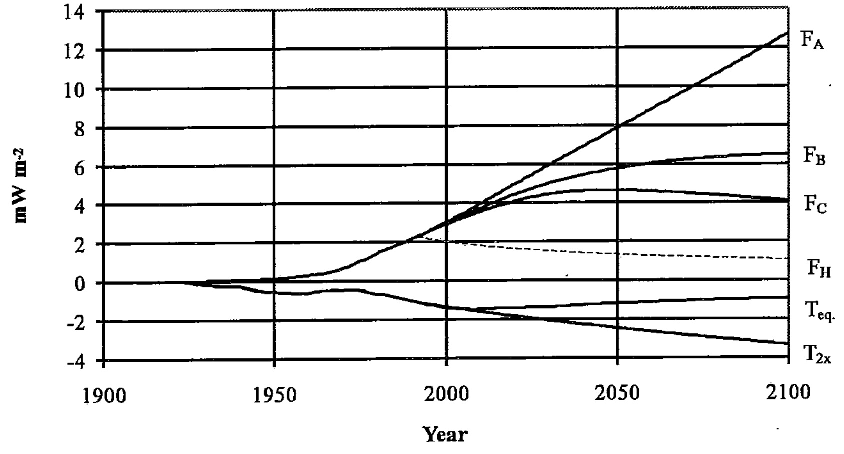

Fig. 2. Radiative forcings calculated on the basis of Finnish emissions and sinks shown in Fig. 1. The impact of the fossil fuel emissions before 1990 is shown with a dashed line (F_H).

The radiative forcing caused by past fossil CO_2 emissions is shown with a dashed line. As can be seen from the curve, 50% of the current (year 1990) forcing caused by the emissions that have taken place before 1990 still remains in the year 2100. Thus it is no great surprise to see that even with fast emission reductions (F_C) the radiative forcing is still almost twice as large in the year 2100 as it is today. The radiative forcing caused by scenario F_B increases only slightly at the year 2100, but at that point its value is almost three times as high as currently. If the Finnish fossil carbon dioxide emissions continue to increase (F_A), the radiative forcing will increase almost linearly.

On the other hand, the carbon sink of Finnish forests has effectively decreased the greenhouse impact caused by Finland. According to the results at the year 1990 their impact compensates 50% of the radiative forcing caused by estimated fossil CO_2 emissions (Fig. 2). Even with an assumed equilibrium in the future ($T_{eq.}$) the negative radiative forcing caused by the carbon sink of Finnish forests remains relatively strong, if it is compared to fossil CO_2 emission scenarios with assumed emission reductions (F_B and F_C). If the fossil CO_2 emissions continue along scenario F_A, the relative significance of the forest sinks greatly diminishes.

Estimates for Finnish methane, nitrous oxide and CFC emissions have been given in *Pipatti et al.* (1996) and *Pipatti* and *Sinisalo* (1994). The CH_4 and N_2O emission estimates are less certain than those of fossil CO_2. Individual emission source categories may have actual emissions that are larger or smaller by a factor of 3 than the ones used. The uncertainty of the sum of the individual categories is on the order of ± 40 %, however. The calculated total direct anthropogenic radiative forcing based on those estimates and the fossil CO_2 emission scenario F_B (Figs. 1 and 2) is shown in Fig. 3.

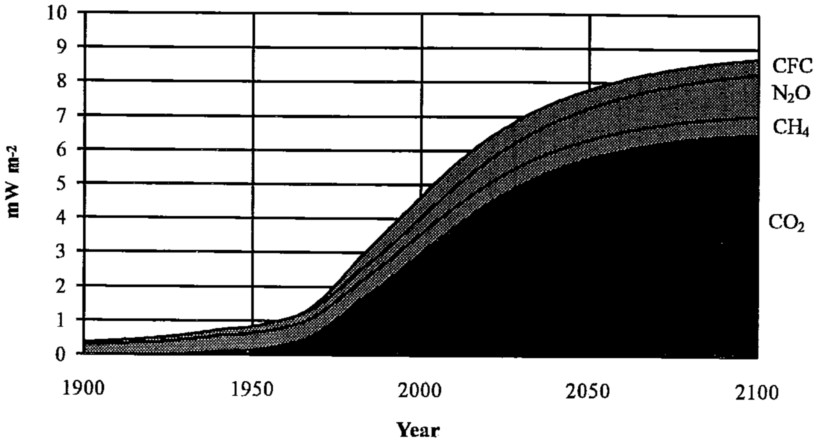

Fig. 3. The estimated total direct radiative forcing due to CO_2, CH_4, N_2O and CFCs and their substitute emissions in Finland. For CO_2 the emission scenario F_B (Fig. 1) is assumed and no forest sink is taken into account.

According to Fig. 3 the forcing caused by methane emissions will remain practically at the current level, while the impact of N_2O increases almost threefold by the year 2100. Despite quite strong reductions of CFCs and even their HCFC substitutes, the total radiative forcing caused by CFCs and their substitutes only slightly decreases during the next century. This is partly due to the assumption that HFC-134a is used to replace all CFCs and HCFCs and partly to the long lifetimes of CFCs. The peak forcing is reached quite soon, in the beginning of next century, however. CFCs destroy stratospheric ozone, which acts as a greenhouse gas, so the net impact of CFC emissions on the radiative forcing is smaller than estimated here.

In addition to direct anthropogenic emissions also the emissions caused indirectly must be taken into account. The estimated emissions and sinks of CO_2 and CH_4 of Finnish peatlands are shown in Fig. 4 along the equilibrium forest sink scenario ($T_{eq.}$) described in the context of Figs. 1 and 2.

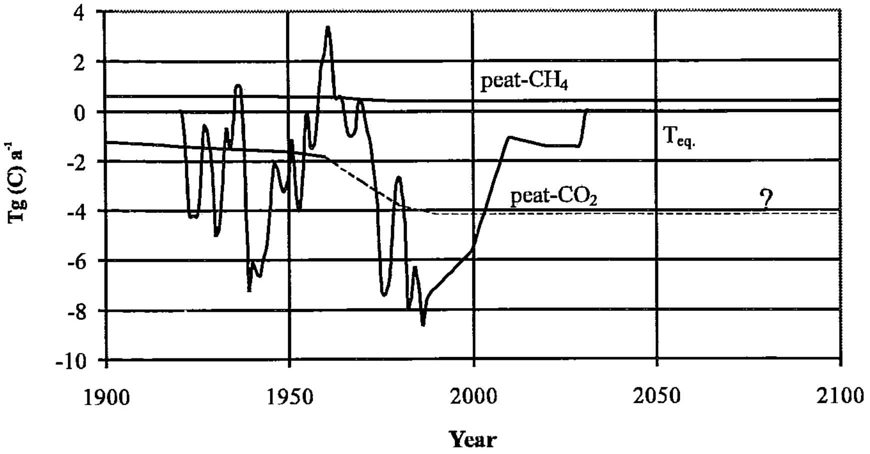

Fig. 4. Estimated CO_2 and CH_4 sources and sinks due to Finnish peatlands and forests. Peat-CH_4 depicts the estimated methane emissions from peatlands and peat-CO_2 is the estimate for the carbon sink of the Finnish peatlands. Scenario $T_{eq.}$ describes the carbon sink into the Finnish forests (Fig. 1). The carbon sink due to peatlands after the middle of the this century (shown with thin dashed line) is very uncertain. The changes in the emissions cause anthropogenic radiative forcing.

Methane emissions from peatlands have decreased by a third from the beginning of the century due to draining for forestry (*Laine et al.,* 1996). At the same time the carbon sink of peatlands has increased considerably according to new estimates (*Minkkinen* and *Laine,* 1996)..This result is quite surprising, and hopefully it can be confirmed by future studies. The values for peatland are based on measurements that cover a period of 60 years after draining.

The calculated radiative forcing due to the anthropogenic alterations to the Finnish biosphere (forests and peatlands) of Fig. 4 is shown in Fig. 5. The estimated radiative forcing due to human caused changes in the Finnish biosphere is presently approximately -2 mW m^{-2}. This can be compared with the estimated 1990 value for total Finnish direct anthropogenic emissions (CO_2, CH_4, N_2O, CFCs and substitutes) of roughly 4 mW m^{-2} (Fig. 3).

The man-made changes of the part of Finnish biosphere taken into account in this study have had a strongly decreasing effect on the Finnish greenhouse impact. The reducing effect has approximately tripled since the 1960s and is approximately as large as the (positive) greenhouse impact of fossil CO_2 emissions at the moment. The minimum has been almost reached already, however, whereas the direct anthropogenic impact is projected to still increase considerably.

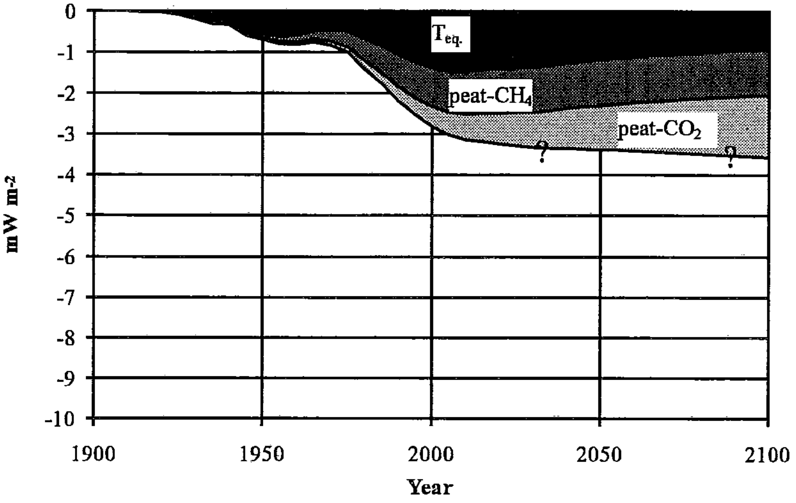

Fig. 5. Estimated total radiative forcing due to changes in the emissions from the Finnish peatlands and forests (Fig. 4). The CO_2 sink in the forest biomass ($T_{eq.}$) and both man-induced reduction in CH_4 (peat-CH_4) and increase in the CO_2 (peat-CO_2) sink in peatlands due to draining for forestry are taken into account. The increase of carbon binding in peatlands due to draining is based on *Minkkinen* and *Laine* (1996).

4. *Radiative forcing per capita*

Another way to use the radiative forcing calculations is to compare the Finnish and global per capita radiative forcings. We have calculated the per capita radiative forcings produced by the IPCC IS92a-f scenarios (*IPCC* 1992) for the year 2100 (Table 2). The per capita radiative forcing targets implied by some stabilization levels (450 - 1000 ppmv CO_2) with some population assumptions are also calculated to the table. The stabilization of CO_2 concentration to most of the levels will take two to three centuries (*IPCC* 1995), but we feel that they nevertheless offer useful range of reference forcings. The IPCC IS92 scenarios include population growth estimates, but the stabilization levels do not. We have used two figures to calculate the per capita forcing, namely the current global population and an population of 11.3 billion by the year 2100, which is the World Bank estimate used in the IPCC reference scenario (IS92a). The reason for the former is that it can be argued that each country should be allowed to cause as much forcing based on its current population, while the cause for the latter is self-evident. Naturally several other possible equity criteria exist (e.g. *Rose*, 1992). The Finnish population is assumed to remain constant. The results based on these assumptions are summarized in Table 2.

Table 2. Estimates for global and Finnish per capita radiative forcings [nW m^{-2} cap^{-1}] in the years 1990 and 2100.

	Finland		Global
	Direct anthropogenic[1]	Biosphere included[2]	
Year 1990	0.7	0.3	0.5
Year 2100	1.7	1.0	0.5 - 0.7[3]
Target (450 - 1000 ppmv), population 11.3 billion			0.3 - 0.7
Target (450 - 1000 ppmv), population 5.2 billion			0.6 - 1.6

[1] See Fig. 3. Population of Finland is assumed to be 5 million.

[2] Net impact of forcings of the Figs. 3 and 5.

[3] IPCC scenarios IS92a-f

The Finnish per capita forcing is somewhat higher than the global average at the year 1990, if the Finnish biosphere component is not included in the calculations (the global figures include all components). If the biosphere is included, the Finnish contribution appears to be lower than the global average. The per capita forcing resulting from the Finnish scenario (Fig. 3) is higher than that produced by any of the IPCC IS92 scenarios, even if the Finnish biosphere is included. The impact of the Finnish biosphere may well be an overestimate, because the carbon sink of drained peatlands in the future is very uncertain.

Compared to the selected stabilization targets (Table 2) it can be seen that if the projected future global population (11.3 billion) is used, the Finnish per capita radiative forcing will exceed the value implied by even the highest stabilization target. If the current global population is used as a base for the calculations, the Finnish contribution is roughly at the same level with the global per capita forcings in 2100. If the lowest CO_2 emission scenario (F_C) is assumed along with low emission scenarios for CH_4, N_2O and CFCs and their substitutes, the direct per capita forcing due to Finnish emissions will be somewhat over 1 nW m^{-2} cap^{-1} at the year 2100 and if the biosphere is also included, the figure drops to 0.4 $nWm^{-2}cap^{-1}$. Thus with very stringent CO_2 emission reductions (F_C) along with reductions in other greenhouse gases and by taking into account human-induced changes in the biosphere it would appear that Finland could theoretically reach the per capita global average by the year 2100.

5. *Discussion and conclusions*

According to our calculations the direct anthropogenic radiative forcing caused by Finnish emissions was on the order of 4 mW m^{-2} at the year 1990. At the same time the global value is approximately 2.5 W m^{-2} (*IPCC,* 1996). From those figures it appears that the Finnish contribution to the radiative forcing (1.6 per mill) is some 60% higher than our share of the global population (one per mill). If the man-made changes in the Finnish biosphere considered in this article are included in the Finnish estimates (as they are in the global ones), the Finnish per capita forcing is smaller than the global. Compared to the IPCC IS92 scenarios it seems likely that the radiative forcing caused by Finland will be higher than the global average at the end of the next century whether we include the impact of the Finnish biosphere or not. Unfortunately the global and Finnish emissions sources and sinks are not exactly the same. Finnish emission estimates do not reach as far to the history as do the global ones which implicitly start from "pre-industrial" year of 1760 in the context of global radiative forcing.

The impact of aerosol precursor emissions is not taken into account in this study, because global average radiative forcing is not well suited for estimating the highly local impacts of aerosols. The SO_2/CO_2 ratio of Finnish power production is only about half of the global average, indicating lower than average aerosol concentrations due to Finnish sources. The higher than average latitude and albedo of Finland also tends to decrease the impact of aerosols.

The prediction of future emissions is notoriously difficult. We feel that with the wide range of scenarios utilized in this work the true emissions will fall between the extremes. Yet some relevant conclusions can be gathered even from the results.

The nonlinearity of radiative forcing with respect to concentration levels for the major greenhouse gases (logarithmic for CO_2, square root for CH_4 and N_2O) causes an overestimation of the future forcings, when the current concentration levels are used, as is done in this work. Some of this effect is countered by the nonlinearity of the carbon pulse response, which acts the opposite way. More important is to recognize the fact that many climate variables do not follow linearly the change in radiative forcing even though global mean equilibrium temperature may well do so. It is also possible that some threshold forcings exist beyond which some irreversible changes in the climate system take place. In this sense these radiative forcing calculations can be thought of only as a continuous, strictly monotonous transformation of the expected eventual change in climate.

The radiative forcing caused by the direct anthropogenic emissions in Finland is increasing rapidly and according to the calculations of this article will remain higher than presently during the next century. The same can be said of the global forcing according to the IPCC (e.g. *IPCC,* 1996) reports. Carbon dioxide is the most significant greenhouse gas, contributing some two thirds of the current Finnish forcing, and even more in the future if the contribution of biosphere is excluded. The sinks and sources of biosphere in Finland are considerable and have relatively large impact on the Finnish radiative forcing.

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